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Scalable energy storage systems for effective electrified mobility concepts

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Abstract

State of the art electrical energy storage systems for passenger cars and commercial vehicles use one type of cell to set up the module and pack level of the battery. The cell type is selected with respect to the specific application and its electrical and mechanical requirements. The number of cells in parallel and in series is defined by the needed energy, power and voltage within the electric power train. Hybridization concepts on battery system level enhance the degree of freedom towards power and energy scalability plus total cost of ownership and battery efficiency advantages. Hybridization here means to use two cell types each one optimized for energy content or power capability to be integrated in specific high power and high energy modules. Finally one has the opportunity to scale power and energy performance on vehicle level. Within this paper the companies AVL and Bosch present their results generated within the European project SuperLIB. The focus is on the evaluation and discussion of general pros and cons for this concept including simulation and hardware test results. Within SuperLIB power and energy optimized lithium iron phosphate cells were used to demonstrate the respective concept for hybridization on module level.

Peer-review under responsibility of Road and Bridge Research Institute (IBDiM)

Keywords: Automotive batteries; EV&PHEV; hybrid battery; lithium-ion batteries

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1. Introduction

Electric vehicles are expected and intended to play an important role for future mobility scenarios because they are compatible with the worldwide need for effective CO_2 savings in combination with the enhanced usage of renewable electric energy coming from wind, water and solar power plants.

So far the technical and cost status of the available energy storage systems are not satisfactory. They have a strong and often dominant impact on the weight, volume and cost of an electrified vehicle. That is why a large number of different electric and electrochemical storage concepts are in the research and development phase besides the well-known systems that are already in the market. The storage elements can differ a lot in their electrical, mechanical, safety and lifetime performance. The linked storage principles on cell level range from double layer storage over primary and secondary electrochemical storage to combinations of them. For on-road vehicles the lithium-ion technology is currently the benchmark in terms of energy density and lifetime performance. Already within that class of electrochemical storage technology we can find a large spread in terms of power and energy capability, voltage level and cell format. Within the final application the overall system performance parameters of the battery are essential. The cell level is not sufficient to be assessed because different chemistries and formats need different efforts on system level to fulfill the requirements coming from vehicle level.

Commonly the power and energy requirements of a storage system have to be covered by performance characteristics defined on the cell level. This often leads to sub-optimal designs requiring over-sizing due to the fundamental trade-off between energy and power capability in electrochemical and electric cells. For a lot of business models linked to mobile applications, the scalability of power and energy in the battery might be done much smarter on system level. Additionally the hybrid approach can help to improve other technical and non-technical performance numbers like the energy efficiency, the total cost of ownership and the environmental impact of an energy storage system. The system level solution can trigger operation modes that are not possible to be triggered on single cell level. This additional dimension can also be used as an enabler for upcoming and new high energy storage chemistries with deficiencies in power and lifetime.

Within the public funded project “SuperLIB”, a European team of researchers developed and evaluated a scalable battery concept for passenger cars and commercial vehicles that can handle modules containing cells with different rate capabilities by implementing new power electronic functionalities. This scalable battery concept is based on high energy and high power storage units that are electrically interconnected on system voltage level via a bidirectional DC/DC converter. The HE and the HP storage element each consists of modules connected in series. The SuperLIB battery has been compared to reference systems that use only one type of cell. Pros and cons for dual cell type batteries in terms of performance and cost will be discussed within this paper - finally coming to conclusions with respect to the developed SuperLIB concept.

Nomenclature

BMS	Battery Management System	NMC	Lithium Nickel Manganese Cobalt Oxide
BoL	Begin of Life	OCV	Open Circuit Voltage
DoD	Depth of Discharge	PHEV	Plug-in Hybrid Electric Vehicles
EV	Electric Vehicles	RTD	Research and Technical Development
ELT	Electrical Loss Time	SME	Small and Medium Enterprise
HE	High Energy	SoC	State of Charge
HEV	Hybrid Electric Vehicles	SoH	State of Health
HP	High Power	TCO	Total Cost of Ownership
LFP	Lithium Iron Phosphate	UC	Ultra Capacitor

2. Technical Background

2.1. Electric storage technologies

Electric and electrochemical battery cells can be classified by their specific storage technology (chemistry), power, energy, capacity and format - related literature can be found elsewhere (Linden & Reddy, 2010). Within one class of storage technology one will often find energy and power optimized cell types. Today the lithium-ion technology dominates the battery market for EV and PHEV applications because of its high specific energy combined with sufficient cycling stability and an appropriate cost per energy and power. In situations when, for example, higher specific power and an even higher energy throughput over lifetime is needed other storage technologies like lithium-ion capacitors or ultra capacitors can be a better choice depending on specific vehicle system and use case requirements. Besides typical behaviors of specific technologies there is still a large variety of cell performances that depend on the supplier. This variety has its origin mainly in different production processes and the specific active and passive material selection. Furthermore cell formats and in-cell electrode arrangements can be very different, often with effects on the overall electrical and safety performance.

The battery design effects discussed in this paper are strongly influenced by the power capability and energy efficiency of the selected cells. The power performance and efficiency of an electrical storage cell can be characterized effectively by its voltage and capacity independent DC resistance, previously called "electrical loss time" (*ELT*) (Imre, 2012) with the physical dimension of one second, according to equation (1). The commonly used DC resistance is defined for typical states and loads, e.g. for: SoC 50 %, 1C discharge rate, 298 K. On the final cell or pack level it is more common to use the power to energy ratio *P*/*E* (equation (2)), here the specific construction of the cell plus lifetime and safety aspects are reflected in the value. Energy efficiencies and operation strategies are better discussed in terms of the respective physical and chemical relaxation phenomena.

$$ELT = \frac{R_{DC} \bullet Q_{reversible}[\Omega * As]}{U_{nominal}\,[V]} \tag{1}$$

$$\frac{P}{E} = \frac{P_{max,10s}[W]}{E_{nominal}\,[Wh]} \tag{2}$$

Power and energy optimized storage cells typically have different *ELT* and *P/E* values. For lithium-ion cells today we can find *P/E* values in the range from 2 to 4 for EV applications, 10-20 for PHEV and 20 to 40 (or even more) in HEV applications. In general *P/E* is different for charge and discharge direction and is strongly depending on temperature and SoC. For future energy optimized storage technologies like lithium metal cells the P/E numbers could be much smaller than for today´s EV cells. Corresponding *ELT* values are somewhere in between 200s (HE) and 10s (HP).

2.2. Battery performance indicators

Within the electric power train the battery system plays a major roll. For pure electric vehicles the battery sub-system dominates cost and driving range related parameters and has an important influence on vehicle lifetime, power, volume and weight. The key performance parameters of the battery and its cells (see Figure 1) define their final layout features. The main requirements come from vehicle system level and from other components within the drive train like the electric motor and the inverter with their specific voltage levels and efficiency tables.

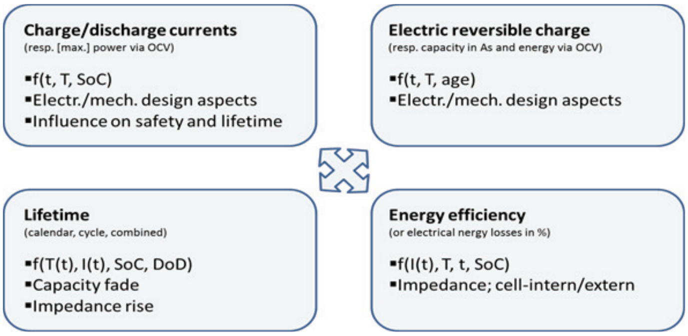

Figure 1: Battery key performance parameters

2.3. The hybridization idea for battery systems

In general hybridization for batteries means to combine different storage elements (in terms of chemistry, *P/E* ratio, *ELT* or voltage) in one battery pack. Hybridization can already start at the electrode level where different types of physical and chemical materials and geometries can store electric charge. In contrast to the hybridization at cell level, battery level approaches can manage to drive the different storage elements by designed electrical connection (passive control) or smart operation strategy via power electronics (active control).

EV and PHEV vehicles of today use one type of storage cell to be integrated in the respective module and pack. The overall battery performance is then directly depending on the cell performance plus additional system level effects. The best systems can only be as good in terms of power, energy and efficiency as the sum of their used cells. Cells have individual characteristic features as e.g. the OCV curve, the internal resistance (versus SoC and temperature) and the characteristic aging functions. One specific vehicle requirement in terms of energy and power can in general only be fulfilled by designing a specific cell for the most important operation point. Normally one would not design a cell for a specific vehicle. Then it is very likely that one has to oversize the overall battery pack in terms of a) energy or b) power. By having a hybrid battery consisting of two different types of cells, the one energy and the other power optimized, one is free to design specific power and energy numbers for the battery pack. The assumption here is that the energy content of the cells is small enough to have the tuning possibility and to reach relevant voltage levels at module or pack level.

Advantages for hybrid electric storage concepts at the system level with respect to single type batteries of the same energy content:

- flexible scalability of battery power and energy
- lower overall aging, especially for the HE storage component → better TCO
- better efficiencies at the storage component level
- better power performance at low and high SoC levels
- broader usable SoC window
- better power performance at low and high SoC levels
- only two cell types to supply all (vehicle) segments (not depending on cell type and nominal voltage)
- energy redundancy because of two separate storage components within the battery
- enabling functionality for new HE technologies with power deficits and/or pronounced aging

On the other hand one has to face the disadvantages of having a higher cost at the system level due to more components being integrated and a more complex battery management because two parts of the batteries have to be managed including the power split with respect to different load cases.

2.4. Different concepts for hybridization

There are different concepts for electric storage system level hybridizations, see Figure 2. The simplest way to perform hybridization is a hard parallel connection of storage components. This principle can be found e.g. on electronic circuit boards where storage components with a small *ELT* number can be found near to the power consuming chip – hard connected to the energy supplying component(s) with a far higher *ELT* value than, for example, a lithium-ion cell. Hard connections of electric and/or electrochemical cells have the disadvantage of the missing current control for the cells and the need for adjustment of the OCV curves. If the OCV curves of the cells/modules do not fit to each other the overall usable energy will be limited. The missing current control for the cells might drive one of the cells/modules to critical operation modes regarding temperature and different SoC states or different impedance aging in the HE and HP part of the battery.

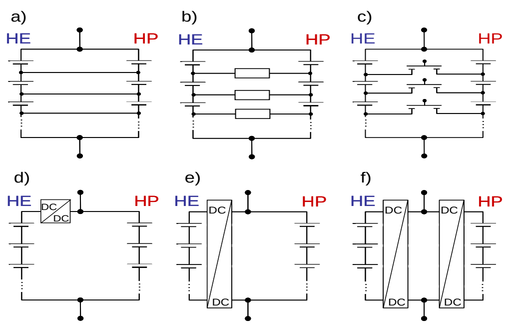

Fig. 2. Examples for hybrid battery concepts: a) to b) passive interconnected parallel cells, c) parallel connection with current control, d) – e) different DC/DC converter concepts on bi-module level.

3. SuperLIB project

3.1. Main Targets

The SuperLIB project had a number of objectives to increase performance of batteries, and make their widespread adoption in transportation, especially automotive, easier by making them more attractive in terms of a number of parameters. The main objectives were as follows:

- Highly integrated battery with lithium-ion HP and HE cells
- Joint package with shared cooling
- Electronic architecture for an efficient energy and current distribution
- Smart energy distribution by advanced battery management
- Extending the useable SoC range of the battery
- Reusability of the pack in passenger EVs and HEVs

The SuperLIB battery is able to offer improved overall performance of the pack, i.e. a better compromise between power and energy density (Gu et al., 2012), and significantly increased lifetime (Mao et al., 2014) by reducing the impact of high currents via successful achievement of the aforementioned objectives.

System performance targets were based on energy intensive traction battery pack requirements such as PHEVs and EVs as defined by the two OEMs involved in the project, i.e. Volvo and Fiat. The targeted applications were respectively a Plug-In Hybrid Bus and the Fiat 500e electric car. These applications require a relatively large battery pack, and substantial power capabilities. From these applications, a single set of specifications has been defined for SuperLIB which was the best possible compromise to match the requirements of both applications (Omar et al., 2013). The main specifications of the SuperLIB battery pack can be found listed below in Table 1, and the battery was designed to be embedded as such in the light vehicle and doubled (in series) for the commercial vehicle.

Table 1. Target SuperLIB system specification.

	SuperLIB
Specific Energy (Wh/kg)	> 75
Energy Density (Wh/L)	> 125
Peak Discharge Power (kW), 10 sec	90
Peak Charge Power (kW), 10 sec	75
Usable Energy (kWh, EoL)	15

3.2. Partner Structure & Approach

The SuperLIB partnership is based on a combination of industry players and research partners. The consortium includes 6 industry participants, 3 research institutes, and 1 SME from 7 different countries. It covers the entire RTD chain with a University institute (VUB), national research and technology organizations (IFPEN, FhG), a private RTD company (AVL), a technology and management consultancy company (K&S), automotive supply industry (Bosch, EB, Valeo EEM) and OEMs (Volvo/VTEC, Fiat/CRF).

The SuperLIB approach was evaluated in real hardware. Lithium ion cells were provided by EB, the DC/DC converter and BMS were developed and produced by Valeo, the bi-module, which shall represent the full battery, was developed by Bosch and assembled by FHG. Several partners jointly developed the BMS application software (Volvo, VUB, IFPEN, AVL). Finally three bi-modules were assembled and tested by the partners Volvo, CRF and AVL (Kurtulus et al., 2015).

4. SuperLIB battery: Technical realization from concept to the final hardware

4.1. The SuperLIB battery concept

In 2.4 different concepts for hybridization have been discussed. Here the SuperLIB concept decision on the basis of first simulations and calculations is explained. Besides serving the electrical requirements coming from vehicle system level (with respect to power, energy and lifetime) the focus was on generating as much benefit from the hybridization idea as possible. In addition, it was decided to run different operation strategies in the test phase of the project in terms of the adjusted HE and HP voltage levels and alternative power split scenarios. Here the energy efficiency aspect plays an important role. Further concept evaluation criteria paid attention to the overall battery volume and weight and not to forget the expected cost level, see Table 2.

Table 2. Decision matrix for the SuperLIB battery concept; the concept characters refer to the ones in Figure 1.

Concept: Evaluation criteria	a)	b)	c)	d)	e)	f)
Weight/Volume	++	++	++	+	+	○
Flexibility to various operation modes	--	-	○	+	++	++
System Efficiency	○	○	○	○	-	--
Cost	++	++	○	+	-	--
Rating result	2	3	2	3	1	-2

Finally concept d) had been selected because of the flexibility for different operation modes in charge and discharge direction by keeping an acceptable level for power electronic integration. With this concept all relevant expected system advantages can be evaluated later on. The choice of concept b) would have led to a more cost efficient solution but also to very restricted operation modes depending on SoC, SoH and temperature.

4.2. Electric battery design

In the SuperLIB battery, the energy optimized storage component is made up of 45Ah cells in a 14S configuration, and the power optimized storage element consists of 7Ah cells in a 14S3P configuration. The battery pack is composed of seven HE modules in series acting as a single string, and similarly seven HP modules in series as a string. The strings are integrated in parallel at pack level. This decision was based on a number of technical reasons:

- Optimization of the total number of electric parts required:
    - one contactor per string, one contactor with precharge for HV path
    - 3 current sensors in total (1 per string + 1 for the total system current)
    - 2 Fuses (1 per string)
- Ability to use a single unreferenced DC/DC converter and Battery Control Unit (BCU), (instead of one for each module in the case of module level electric integration of HE/HP strings).

One Module Control Unit (MCU) is used to control each HE and HP module for measurement of cell voltages and temperature, as well as integrated cell balancing. The rationale for this decision was easier integration with each sub-module, and shorter wire lengths.

4.3. Mechanical and thermal design

The design of the modules (see Figure 3) and the overall battery pack had to pay attention to the electrical and mechanical specifications of the SuperLIB battery. It had to serve for the two addressed applications with their specific load profiles and the related thermal losses by keeping the possibility to test different operation strategies (regarding HE and HP power split) later on. The mechanical battery development had been an iterative process in between mechanical design and the related thermal simulations by adjusting materials, components and cooling paths.

The following main constraints and layout features were derived:

- The modules consist of serial strings with purely high power or high energy cells
- The high energy modules have a nominal voltage of 44.8 V (14S) and a nominal capacity of 45 Ah
- The high power modules have a nominal voltage of 44.8 V and a nominal capacity of 21 Ah (14S3P)
- The parallelization between HP and HE storage elements is performed at the module level
- The modules use water/glycol as cooling fluid
- The SuperLIB battery has a nominal voltage of 314 V and a nominal energy content BoL of 20.7 kWh
- Aluminium plates in between the cells are used to pick up most of the released heat and serve for temperature homogeneity on the cell surface
- Ultrasonic welding is used for interconnecting the HE cells, and clinching for the HP cells

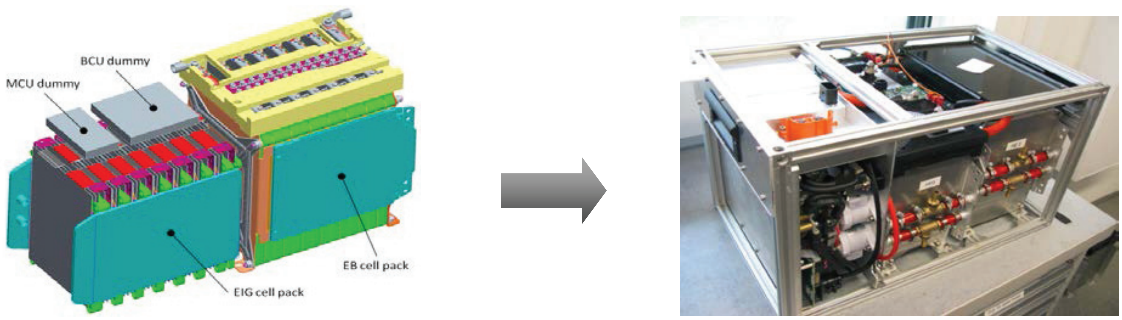

Fig. 3. The construction of the SuperLIB HE and HP modules and the overall double-module integration.

4.4. Testing (real life and virtual)

Another important part is validation of the concept via “Virtual Vehicle Testing”. The testing setup (Figure 4) has a detailed model of the Fiat 500e electric vehicle, where the vehicle and power train model is implemented to run in real time in combination with a battery tester so that the battery can be tested in closed-loop in a realistic environment with proper electrical and thermal conditioning boundary conditions for various use cases. Results of these tests, which include various regulated driving cycles as well as real world driving situations in urban conditions, are presented in the following section.

Fig. 4. Battery in the loop testing with AVL InMotion-Visualization Inferface (left) and testbed setup for battery in the loop testing (right).

4.5. Results

Various regulated driving cycles were tested to get an understanding of bi-module behavior in standard tests. In addition to these drive cycles, it was also important to get a view on real world driving; and the “AMS-E-Runde” was used for this purpose (Figure 5). It is a round track in the area of Stuttgart which is named after the German automobile magazine “Auto Motor und Sport”, where it is frequently used to test electric vehicles. It comprises urban as well as country roads and has a length of approximately 14 km.

“AMS E-Runde” testing results are presented below in Figure 6. It can be clearly seen that all the regular power demand peaks are completely covered by the HP string, and the HE string is only used to supply energy for relatively long discharge parts of the driving profile.

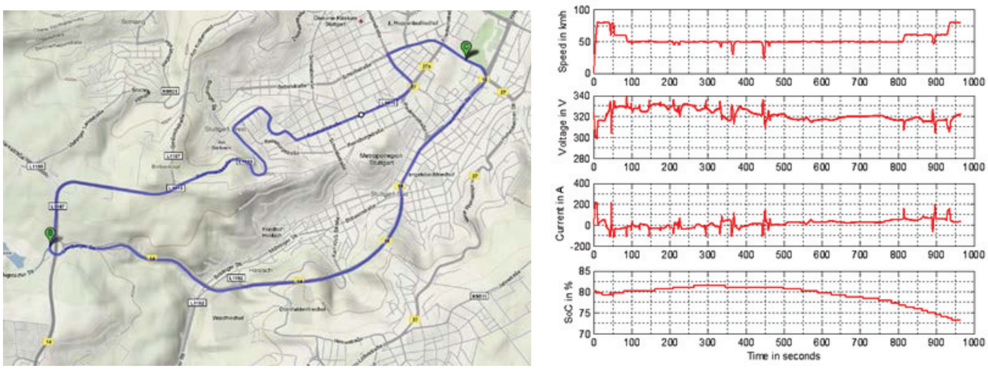

Fig. 5. Overview of the AMS E-Runde (left) and Driving and Battery Parameters of the AMS E-Runde (right).

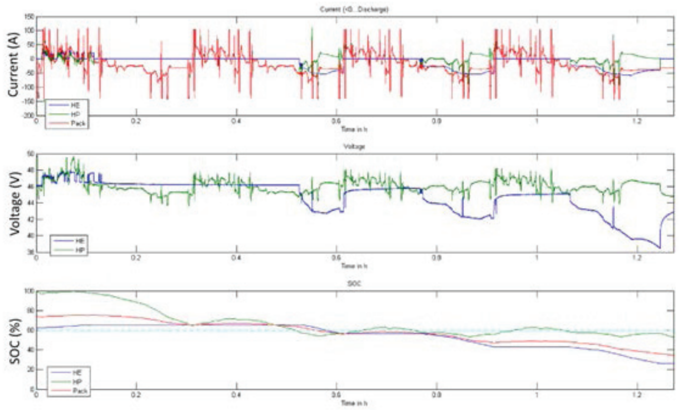

Fig. 6. Measurement from the Bi-Module during battery in the loop testing with AMS E-Runde profile.

4.6. Performance and cost examination versus state of the art

In the end phase of the project comparative examinations had been set up to generate general messages as precise as possible. To do so is not trivial because of the uncertainties in cost functions with respect to cell format, technology, aging, system integration, production volume, production processes, cooling concept, etc. and the huge spread in requirements for passenger cars (e.g. EV: somewhere in between Renault Twizy and Tesla Model S) and also for commercial vehicle (Bus and Truck with different operation scenarios) market segments.

Within SuperLIB the battery system level price calculations have been done on the basis of generalized data for batteries from market studies (Pillot 2014) independent from chemistry. The electrical performance calculations result from real cell data (data sheets and own measurements). For the battery pack a portion of 70% (without power electronics) in volume has been assumed for all kind of cells. In Table 3 some of the calculated values are shown: The Fiat 500e data shows the situation for the (virtual) Fiat 500e pack with its 63Ah prismatic cells. Line 2 shows the case for the SuperLIB hybrid battery with its 3 HP 7Ah cells in parallel to one 45Ah HE cell. In the last line the result for a requirement optimal (with respect to Fiat 500e power and energy) share between HE and HP cells is shown.

Because of the HP cell related higher price for energy and the lower energy density, hybrid concepts reveal higher cost and lower energy density when working with state of the art cells in the Fiat 500e. On the other hand reduced aging and a broader SoC window combined with business case scenarios for higher production volumes lead to a smaller price level in the end. Without the volume effect the SuperLIB concept shows no significant price advantage for the passenger car scenario here. For other vehicle platform cost functions and other cell types the results can be significantly different. Especially for (future) HE and HP type cells, the price can change significantly with respect to technology and with respect to production volumes. The production volume argument also implies the option to take advantage of modularity and scalability benefits. The exemplary price assignment for the Fiat 500e in Figure 7 starts from the battery level (see Table 3).

Table 3. Exemplary calculations for battery system level related price and electrical performance including the battery price numbers from the Avicienne report (Pillot, 2014) and the Fiat 500e reference. (EB: European Batteries Company // 3P: number of 7Ah HP cells in parallel).

	Price **Euro**	**Peak Power** **kW**	**Cont. Power** **kW**	**Spec. Energy** **Wh/kg**	**Energy Density** **Wh/l**	**Energy** **kWh**
Fiat 500e	6875	85	44	88	170	22,9
SuperLIB 3P	8685	134	111	83	142	20,7
SuperLIB opt.	8400	85	72	91	151	22,9

The 100% line in the graph is always related to the single cell reference pack. The second bar in the graph is related to the cost scenario reflecting a design to lifetime and range, the third bar is related to additive cost advantages that arise from expected higher cell production volumes by gaining from just 2 cell types that serve all mobile vehicle market segments.

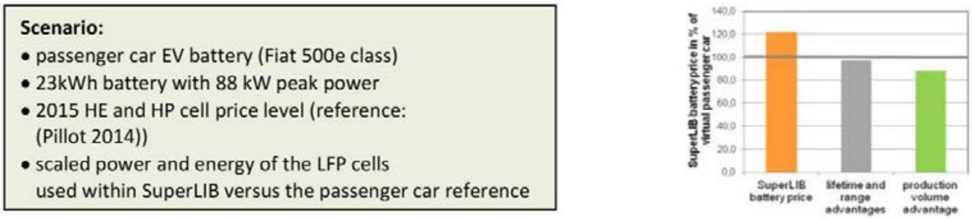

Fig. 7. Relative battery price level for a SuperLIB battery relative to the Fiat 500e passenger car. Cell and pack prices are related to the numbers mentioned in the Avicienne report of the year 2014.

5. Conclusion

The SuperLIB project has achieved its main targets by developing a system architecture that combines the benefits of both high-power and high-energy cells into one compact system that is targeted to be used in future EVs. Besides the conceptual design and extensive modelling and validation of battery cells characteristics, the project developed functional prototype ”bi-modules”. Bi-modules were tested on test beds to confirm performance under standardized test conditions as well as under virtual real road conditions to demonstrate feasibility of this new concept. The concept was benchmarked with state-of-the-art technology and with respect to cost.

Finally the SuperLIB battery concept exhibits a potential for lifetime and cost improvement on system level, independent from EV, PHEV and HEV market segments. In addition the SuperLIB concept revealed clear advantages in terms of power to energy scalability and power characteristics for challenging operation modes like low temperature and low SoC levels. Furthermore hybrid battery systems could be the key for using new cell technologies in future mobile applications.

Acknowledgements

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